

New Techniques for Visualizing 3D Field Lines and Particle Trajectories

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Abstract. In many areas of science and engineering, an essential task is to model and understand complex flow phenomena from the evolution of the universe, patterns of ocean flow, aerodynamic flow surrounding a vehicle, down to the functioning of ecosystems. One way to depict a flow field is to use field lines and particle trajectories, which are straightforward to compute and render. However, choosing the right set of field lines or trajectories that best convey the flow structure and dynamics is a nontrivial task. This paper presents four new techniques easing this task and discusses how these techniques can enhance scientists' ability to understand and explain data generated by their simulations.

1. Introduction

Flow simulations generate both scalar and vector field data, and those also tracking Lagrangian particles add particle data. A common approach to visualizing a vector field is to compute field lines characterizing the flow pattern and structure. Similarly, scientists trace particles and follow the trajectories to understand the dynamic behaviors and stability of the flow. Most flow visualization tools provide functions to compute field lines and trace particles. Rendering of the lines and trajectories is straightforward. With the growing processing power and capacity of supercomputers, scientists are able to model more complex flow at increasingly higher resolutions. The resulting vector fields and particle data become challenging to visualize and understand for two reasons:

1. The visualization could easily become cluttered if too many field lines or particle trajectories were used.
2. Choosing and plotting representative field lines and trajectories could become a tedious and laborious task for the scientists when the intent was to use a smallest number of lines or particles to depict the flow.

In this paper, we describe four new approaches to flow visualization using field lines and trajectories:

1. View-dependent field-line visualization [1].
2. Locality-based visualization of particle trajectories [2].
3. Sketch-based classification for vector field visualization [3].
4. Dual-space analysis and visualization of particle trajectories [4].

These methods have been shown to be effective in visualizing large, complex flow fields commonly found in a wide variety of applications.

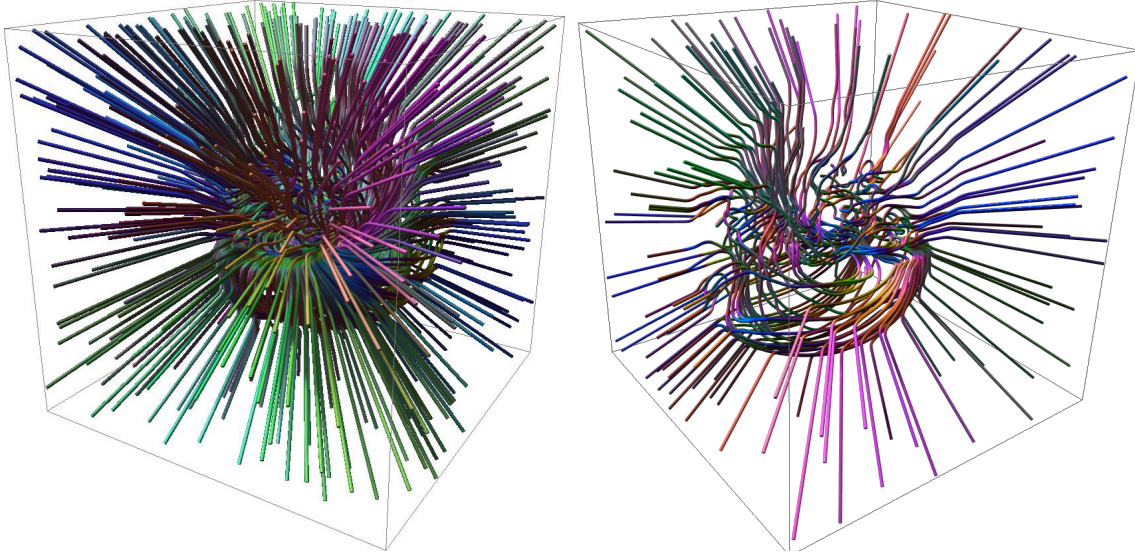


Figure 1. Streamline visualization of the velocity field from a supernova simulation. Left: view-independent visualization based on random seed placement; right: view-dependent visualization that effectively conveys the flow structure in a clutter-free fashion. The data set was provided by John Blondin at the North Carolina State University.

2. View-Dependent Field-Line Visualization

When visualizing a complex flow field, a simple approach is to use a large number of field lines to capture all the essential aspects of the flow. The process begins by placing seed points uniformly or strategically spreading the domain. From these seed points, field lines are traced. This step may be done automatically based on some criteria or manually by the user based on his domain knowledge. If the number of field lines is large with respect to the display space, the picture becomes cluttered, and occlusion prevents us from seeing many important flow features. Clutter may be reduced by uniformly or adaptively dropping field lines according to some importance measures of the flow property, but suppressing occlusion is best done in a view-dependent way.

We have developed a new field-line visualization algorithm that uses view-dependent measures of each field line, leading to intelligible, uncluttered pictures that effectively capture the intrinsic structure and pattern of the flow [1]. Figure 1 shows streamline visualization of a supernova generated without and with using our algorithm. The algorithm consists of four steps:

1. Generate a pool of random field lines.
2. Compute the screen occupancy of each field line to determine which areas of the screen are highly occluded and which areas are not.
3. Prune those field lines contributing to visual clutter. This is done by taking into account the occupancy data as well as some importance measures of the lines.
4. Optionally add streamlines to areas that have no or very few streamlines.

Note that this process may be completely automatic and does not require any user input. This work shows that the use of both view-independent (i.e., data space) and view-

dependent (i.e., image space) information to construct visualization often leads to better results. For visualizing large complex flow fields, this approach is particularly attractive.

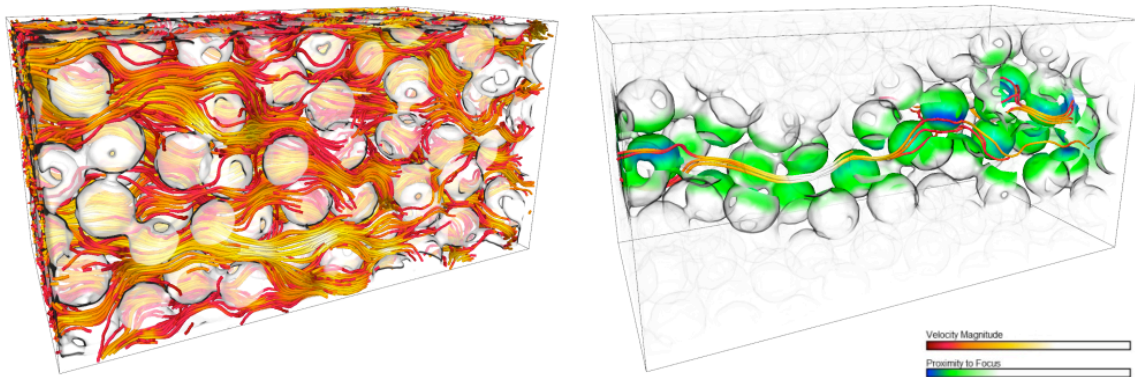


Figure 2. Pathline visualization of groundwater data. Left: conventional method; right: locality-based visualization both displaying selected trajectories and providing explicit visual cues of the trajectories' proximity to the surrounding solid surfaces. The data set was provided by Tim Scheibe at the Pacific Northwest National Laboratory.

3. Locality-Based Visualization

In many flow simulations, the behavior and properties of particle trajectories depend largely on the physical geometry contained in the simulated environment. The ability to inspect the flow around geometry is crucial to the overall understanding of the simulated phenomena. Previous work has often utilized focus+context rendering techniques, with an emphasis on showing trajectories while simplifying or illustratively rendering the physical areas. However, when the geometry is complex or spreads the whole spatial domain, conventional techniques no longer work well. We have developed a locality-based visualization technique to address this problem [2]. The motivating application is groundwater simulations, and the scientists we are working with model fluids moving through porous media, which are solid grains. The amount of such solid surface accounts for a considerably large portion of the physical space, as can be seen in the left image of Figure 2. The solid grains making up the geometry act as a barrier for the flow particles. In this single species simulation, the geometry can direct the particles to twist and turn several times as they navigate their way around the barriers.

Locality-based visualization, based on a distance volume computed from the solid geometry, provides a means for understanding how a trajectory's behavior correlates to the surrounding surfaces and for visualizing locally significant properties of the flow. In addition, a supplemental view, a modification to 2D curve plots, is also provided to help illustrate divergences in trajectory values over time. The user can select trajectories using a linked warped curve plot that can be configured with respect to any given or derived property. The visualization displays selected trajectories and the surrounding surfaces using color-mapped rendering that does not occlude the trajectories of interest. An example is shown in Figure 2, which contrasts standard pathline visualization with locality-based visualization of data from a groundwater simulation. The particles were selected because they exhibited a high velocity magnitude at a specific location along the major flow direction. This region in particular is seen where the trajectories are colored

white. A single trajectory is selected as the focus. Where the flow line is moving quickly, it is also far from the surfaces.

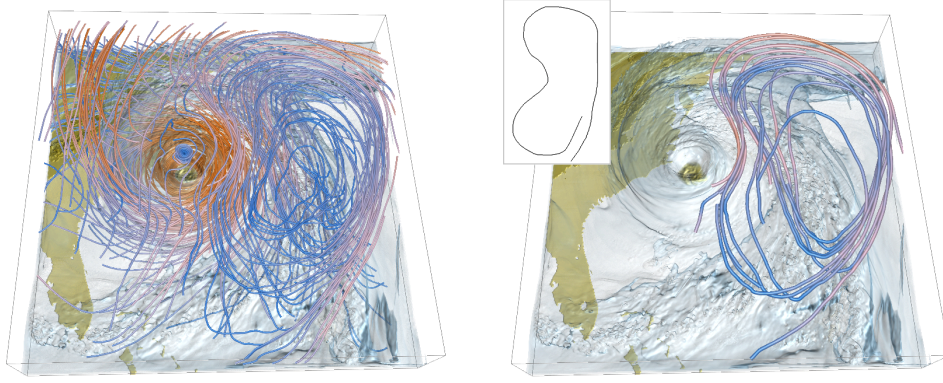


Figure 3. Streamline visualization of a hurricane simulation. Left: conventional method; right: sketch-based visualization highlighting features of interest.

4. Sketch-Based Classification and Visualization

It is desirable to classify field lines and trajectories and view them selectively according to the purpose of analysis or presentation. If the classification is properly done, the results can take the scientists directly to features of interest. The classification can also help solve the visual clutter problem since irrelevant patterns such as more uniform flow or small-scale features may be discarded. We have developed a user-centric approach to visualizing large, complex vector or particle data based on classification of field lines and trajectories [3].

Our approach is based on the design of an intuitive sketch-based interface, through which the user specifies a flow pattern of interest by simply sketching a 2D curve. A preprocessing step traces a large number of field lines to thoroughly cover the vector field under study. The input curve is then compared with this set of field lines by using a string matching method, and the system presents matching field lines, as shown in Figure 3 for the study of a hurricane simulation. This interface is also suggestive based on a pre-clustering of all the field lines. That is, when the user specifies a particular curve, in addition to the best matching kind, the interface also displays a few other similar ones. It is also possible to prune field lines based on scale. After exploring, extracting, and examining several groups of feature field lines from the data, the user can create visualizations by compositing the desired, representative groups into a single picture while leaving out unimportant ones to most effectively use the display space. This sketch-based visualization method assisted with automatic clustering thus offers scientists more expressive control in visualizing complex vector field and particle data.

5. Phase-Space Clustering and Visualization

It is often advantageous to also visualize the trajectory data in a novel space other than the physical one. One such example is shown in our locality-based visualization work [2]. We have developed a dual-space visualization approach to the analysis of particle data [4]. By examining different patterns of time series curves in the phase space of the data along with depicting the particle motion in the physical space, scientists

can more easily confirm several hypotheses they had about, in the case of combustion simulations, the interaction of the turbulence with the flames and ignition kernels.

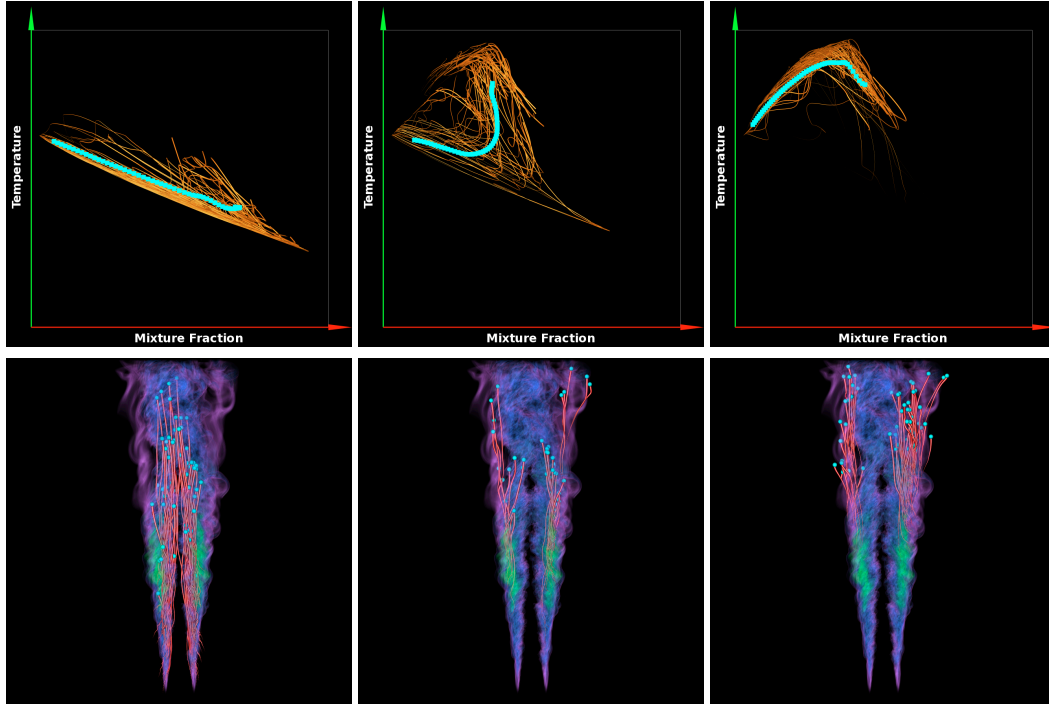


Figure 4. Visualization of three selected groups of particle trajectories computed from a turbulent combustion simulation. Top: phase space visualization; bottom: corresponding physical space visualization. The data set was provided by Jacqueline Chen at the Sandia National Laboratories.

In our work, the phase space is composed of the particles' attributes parameters, specifically, temperature and mixture fraction. The physical space is the 3D simulation domain, in which the particles are advected. The first step is to cluster time series curves based on their shapes and positions in the phase space. Next, the scientist can tune the clustering parameters through an interactive interface to refine the clustering results based on his domain knowledge. The scientist then can browse through and compare individual clusters while visualizing the movement of corresponding particles in each cluster to verify his understanding or hypothesis, as shown in Figure 4 for selected clusters of particle trajectories in a turbulent lifted autoignitive ethylene/air jet flame.

Automatic cluster analysis is a critical component in our system. There are two major groups of clustering algorithms: similarity-based and model-based. To support interactive visualization, we choose to use the latter because of the higher computational complexity of the similarity-based method, which also needs a careful design of appropriate similarity metrics for specific applications. Although we have applied this method only to the analysis of combustion simulation data, the method is also attractive to anyone who needs to analyze particle trajectory data.

6. Summary

Visualizing vector field remains a challenging problem. We describe four novel techniques designed to support the analysis and visualization of large, complex vector fields and particle data. Through our participation in the U.S. Department of Energy's SciDAC (Scientific Discovery through Advanced Computing) program, we were able to deploy and accurately assess these techniques with our science collaborators who conduct large-scale astrophysics, turbulent combustion, fusion, and groundwater simulations.

As discussed in Section 2, the groundwater scientists are interested in understanding the effects of localized zones of relatively low velocity (immobile zones) within the pore-scale flow field, and their effect on transport phenomena at larger scales. Our technique helps them understand and quantify the nature of these zones at the pore scale, and their larger-scale effects. The locality-based methods provide visual clues to a selected fluid particle's proximity to solid grain surfaces, which is directly associated with its velocity since grain surfaces are no-slip (zero velocity) boundaries. Evaluation of the time spent by a particle in slow and fast zones, and the temporal/spatial correlation of these zones, provides a basis for developing upscaled representations of particle transport times that are physically meaningful.

As discussed in Section 5, the combustion simulation scientists have benefited from the capabilities of dual-space trajectory clustering and visualization. They usually have several hypotheses about the nature of the particle trajectories, but were unable to determine if the particle data was consistent with their expectations, nor were they able to present the particle data coherently to the combustion community. The ability of the dual-space system to interactively partition the trajectories depending on suggested trajectories is key to hypothesis testing. The resulting visualizations provide detailed information regarding the evolution of fluid parcels traversing a turbulent autoignitive environment.

We hope our successes will prompt others to extend our methods or develop new ones with similar approaches. It should be straightforward to integrate these new techniques into existing scientific visualization tools to drastically enhance scientists' ability to cope with the complexity and scale of their data.

Acknowledgments

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